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METHODOLOGY INVESTIGATION

FINAL REPORT

OF

NEUTRON DEVICE MONITORS

CRAIG R. HEIMBACH

TEST AND RESEARCH DIVISION
NUCLEAR EFFECTS DIRECTORATE

U.S. ARMY COMBAT SYSTEMS TEST ACTIVITY
ABERDEEN PROVING GROUND, MD 21005-5059

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Various diodes have been investigated as monitors for 1 MeV equivalent neutrons. One particular diode, the DN-156, has proved suitable. It is not sensitive to thermal neutrons or gamma rays. Production uniformity is sufficiently good that batch calibration is suitable, and individual device calibration is not necessary. The device is not temperature stable, so precautions must be taken to obtain correct results. The DN-156 has been used to calibrate a test reactor neutron field to 9 percent, traceable to a national standard.

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MEMORANDUM FOR Commander, U.S. Army Test and Evaluation Command, ATTN: AMSTE-TC-M, Aberdeen Proving Ground, MD 21005-5055

SUBJECT: Methodology Investigation Final Report of Device Monitors of Neutron Damage, TECOM Project No. 7-CO-R90-APO-010, Report No. USACSTA-7005

1. REFERENCES

Memorandum for Commander, subject: FY90 RDTE Methodology Improvement Program Grant, dated 2 October 1989.

2. BACKGROUND

a. Neutron dosimetry for radiation-effects testing is reported in terms of 1 MeV equivalent fluence. This is found by integration of the neutron spectrum over a silicon response function, so that the reported fluence correlates with damage in silicon devices.

b. Finding the neutron spectrum is often quite difficult. For example, a reactor may be pulsed, releasing the neutrons in a few microseconds or milliseconds. The working volume may be constricted as inside a radio or missile. The time may be limited by the availability of the test item to only a few days or weeks. Each of these conditions make spectral determination, either by spectroscopy or by foil activation, infeasible.

c. An alternative to spectral measurement is the use of a dosimeter whose response is intrinsically 1 MeV equivalent. For example, the current gain of a transistor or forward voltage of a diode might be used to monitor neutrons. Difficulties with this approach include finding devices which are sufficiently uniform for batch calibration, whose response is limited to neutrons and not sensitive to other environmental variables, and which can be simply and accurately read out.

3. TEST OBJECTIVES

a. A promising device for neutron monitoring had been identified before the methodology program began. This was the HARSHAW DN-156 PIN diode. The objective of the program was to develop and prove procedures for the use of the device.

b. Should the selected device prove unsuitable, alternate devices were to be investigated.

4. SCOPE

a. A suitable readout technique had to be demonstrated for the DN-156. This technique had to be one which was easily done and insensitive to minor variations in procedure. The procedure suggested by the manufacturer proved suitable.

b. Batch uniformity had to be tested. This would allow the use of a device without individual calibration, greatly easing the overall procedures.

c. A lack of sensitivity to environmental variables other than neutrons had to be demonstrated. These variables would include gamma rays, temperature, and the time interval from exposure to readout. Should these variables have an effect on the ultimate reading, correction techniques had to be developed.

d. The device had to be shown to respond properly to neutrons.

5. SUMMARY OF RESULTS

a. The DN-156 has been shown to be suitable as a 1 MeV equivalent neutron monitor. The Army Pulse Radiation Facility (APRF) fast-burst reactor at USACSTA was recalibrated with the device. Results were consistent with previous measurements. Enclosure 1 reports the results on the DN-156.

b. Other potential devices were identified. Enclosure 2 summarizes these results.

6. CONCLUSIONS

The DN-156 is a useful device for 1 MeV equivalent monitoring. It can be used to obtain quick and accurate measurements in reactor environments.

7. Point of contact for this action is Dr. Craig R. Heimbach, DSN(AV) 298-4882, (301) 278-4881.

FOR THE COMMANDER:

A. H. KAZI
Director, Nuclear Effects
Directorate

3 Encls
1. Use of Neutron-Sensitive Diodes Monitors for 1 MeV Equivalent Neutrons
2. Investigation of Various Diodes as Neutron Monitors
3. Distribution List

THE USE OF NEUTRON-SENSITIVE DIODES AS MONITORS FOR 1-MeV EQUIVALENT NEUTRONS

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1.0 Introduction

Neutron dosimetry can be accomplished by measuring the neutron spectrum and integrating it over a desired response function. For neutron damage to silicon electronic devices the appropriate damage function is the 1 MeV equivalence function defined in Reference 1.

An alternative approach explored here is to use a silicon device as a neutron damage monitor. Since the device is silicon-based, it is by definition damaged in accordance with the silicon damage curve. The 1 MeV equivalent fluence can be determined by comparing the damage in the unknown environment versus the damage induced by a known radiation field, such as a national standard.

This approach has several advantages, and some potential pitfalls.

The primary advantage is ease of use. Several devices can be used to map a radiation field, including the interior of test objects, in one neutron exposure. This is far easier, and the results more quickly available, than the use of active spectroscopy or activation foils for spectrum determination. This ease of use would spur more frequent comparisons with national standards and intercomparisons with other facilities. Also, no spectrum calculation is required as is desirable with foil activation techniques.

The use of such a device has in the past run into one of several pitfalls. Many device production batches are not very uniform, so that each device must be individually calibrated. The device may be sensitive to characteristics of the environment other than neutrons, such as gamma rays or storage and readout temperatures.

A diode manufactured by Harshaw, the DN-156, has been tested as a neutron monitoring device. Tests were performed to investigate gamma-ray and temperature dependence, fading, and 1 Mev equivalence. With careful use, the DN-156 can serve as a reliable neutron damage monitor.

2.0 The DN-156

The DN-156 is a PIN diode made commercially by Harshaw/Filtrol (2). It is a 3.5 mm long by 3 mm diameter cylinder with 9 mm long leads. Since the response is due to permanent displacements in the lattice, it is used passively.

The major use of the DN-156 is as a neutron-sensitive health-physics monitor for high-level personnel dosimetry.

3.0 Read-out Procedure

The read-out procedure has to be one which is easily done. Also, it should be one where small variations in the procedure have small effects on the result.

The read-out procedure used to measure the damage in the DN-156 was to inject a 6 millisec, 25 milliamp, forward current pulse into the diode. The forward voltage drop is measured to the nearest millivolt in the middle of the pulse. The data for record is taken on the third pulse.

Since a voltage drop is being measured on the current injection, it is quite simple to use calibrated resistors to verify the magnitude of the injected current pulse. An oscilloscope is used to verify pulse width.

Figure 1 shows typical forward voltage readings taken at various times after exposure to neutrons. There is a decline in the voltage for each successive reading. For readings taken one hour after exposure, this decline is relatively steep. For readings taken after 24 hours, the decline is relatively small.

The procedure used for readout is to use the forward voltage measured in the third pulse. Readings at times other than 24 hours after exposure are corrected to 24 hours.

Tests were done to establish readout sensitivity to variations in either pulse height or pulse width. The readout was found to be sensitive to pulse height. The variations in output was found to be proportionally less than variations in pulse height, however. Since it is possible to calibrate the system to one part in a thousand with a precision resistor, the effect of pulse height error can be made less than 0.1%. No variation in output was found when varying the pulse width from 4 to 8 msec, within the precision of the measurement (2%).

It was also found that readings taken before the 24-hour read had only a small effect on the 24-hour read, so that preliminary readings may be taken sooner and not interfere with the official 24-hour results. Figure 2 shows the results of eight diodes exposed

simultaneously to the same neutron fluence. Four of the diodes were read at 24 hours with no prior reads. The other four were read out at 24 hours with the number of prior reads varying from 3 to 70. The diodes with pre-reads averaged 2% lower than the diodes with no pre-reads. The worst-case deviation was 4%.

The readout procedure tested above is one recommended by Harshaw. Once the correct readout procedure was determined, the consistency of the production lot could be tested. It was 2% (1 sigma). This is such a tight tolerance that calibration of a batch of diodes can be used in place of individual diode calibrations.

4.0 Temperature Dependence at Readout

The forward voltage is a function of the temperature at the time of readout. This was determined by exposing a group of diodes to neutrons and performing readout at various temperatures. A temperature-controlled box was used which contained the diode and connectors, but which did not contain the readout electronics. Pre-readout calibrations were performed with the resistors, as usual. The results are shown in Figure 3. From this data a readout correction of

$$V(25) = V(T) - k * (T-25) * (V(25)-V_o) \qquad (1)$$

is obtained, where V(T) is the forward voltage measured at temperature T in degrees centigrade and V_o is the zero-dose forward voltage (typically 1.55 volts). The value determined for k was 0.0048 +-10%, which is consistent with the manufacturer's data sheet.

This is a small correction for most measurement situations. It amounts to only a 2.5% correction for the range 20 to 30 degrees centigrade, which would cover a standard laboratory environment. Caution must be used in handling the device, however, since bringing it up to body temperature could cause a large error. It has been found that there is about a 5% increase in forward voltage if the diode is held in the hand for a minute, and that the diode recovers to ambient in about 20 sec.

In equation 1, the zero-dose forward voltage is subtracted from V(25) because only the incremental voltage added by the neutron exposure is affected by the parameter under study. Similarly, for the fading and storage temperature effects discussed below, the relative readings refer to readings with the zero-dose voltages subtracted. Obviously, a diode will not fade below its zero-dose voltage.

5.0 Fading

5.1 Room Temperature

So long as the diode is consistently read out at 24 hours after irradiation, there is no need for a fading correction. However, it is desirable to be able to make the readout at other times. A fading curve was developed to adjust readings made at times other than 24 hours to the 24-hour calibration point. This curve is shown in Fig. 4. It was found not to be sensitive to neutron fluence. Using this curve, diodes may be read out from 1 hour to several weeks after exposure.

The fading curve was found to depend on the manufacturer's lot. The variations were less than 5% at any time up to 48 hours after exposure, but for best accuracy, a separate curve should be found for each diode batch.

5.2 Other Temperatures

The above data was taken for diodes held at 25 degrees centigrade from exposure to readout. Further testing was done at alternate temperatures to see the extent to the fading varied. It was found that heat accelerated the fading and that cold retarded it. Fig. 5 shows the results of fading measurements when the diodes were exposed at 25 degrees, stored for various times at other temperatures, and then read out at 25 degrees. The result depends strongly on the temperature history of the diode. Storing the diode at high temperatures causes exceptionally high deviations.

These temperatures are not likely to be seen in most test environments, but they may be approached in shipping the diodes from the point of irradiation to the point of readout. Shipping could cause large uncertainty in the results unless the temperature is controlled, or unless the temperature is monitored and adjustments made for variations.

Heat treatment of diodes can anneal out much of the shallow damage and make the readings must less susceptible to fading or to variations due to storage temperature. For example, a readout procedure was tested where the diodes were read out 1 week after exposure. Before readout, the diodes were heated for one hour at 100 degrees C. The diodes gave the same result within an uncertainty of 2% irregardless of storage for 24 hours at temperatures ranging from -12 to +50 degrees C. If exposure or storage temperature are problems, such a procedure can reduce uncertainties. Also, this procedure can form the basis of facility comparisons by mail.

6.0 CALIBRATION

Preliminary investigations showed that the diode damage saturated above 1.0E+12 n/cm**2 (1 Mev). Above this level, there was little voltage change for extra neutron exposure. Therefore a calibration curve was developed for neutron fluences only up to about 1.0E+12.

The calibration was done by exposing several sets of diodes to neutrons at the Aberdeen Pulsed Radiation Facility (APRF) reactor. All exposures were at the same distance from the reactor. Only the time of exposure was changed. The 1 MeV equivalence scale was normalized by exposing three pair of diodes to a standard Californium-252 source at the National Institute of Standards and Technology (NIST). Thus the shape of the calibration curve (Figure 6) was determined by the APRF reactor, and the scale was determined by the NIST exposures.

The uncertainties in the NIST exposure are due to source strength (2%), scattering (<1%), distance(<1%), temperature and fading correction (1.5%), and diode consistency (2%), for an overall uncertainty of 3.5%. The uncertainty in the remainder of the curve is due to ability to monitor relative neutron fluence (2%), diode consistency (2%), and uncertainty in the NIST calibration. The overall uncertainty in the curve is thus 4.5%.

In Figure 6, there are two calibration curves. These two curves are from two different manufacturer's lots, and differ by as much as 12% in their reading for a given exposure. These differences are significant. For best accuracy, a separate calibration curve should be developed for each diode batch.

It should also be noted that the calibration curves are not linear. This nonlinearity is in the diodes, and not in the readout equipment.

7.0 Gamma-Ray Sensitivity

In any test environment with neutrons, there are also gamma rays. It is desirable for a neutron monitor not to be sensitive to these gamma rays. The DN-136 was tested for sensitivity to gamma rays by exposing some to massive amounts of gamma rays either before or after neutron exposure to see the extent to which this would alter the readings.

Table 1 is a record of these exposures. Three diodes were exposed to 122 kRad(Si) from Co-60. The increase in forward voltage corresponded to 2.6E+9 n/cm**2. This is a negligible effect for most environments used for neutron testing of electronics.

After the neutron exposure, all the diodes were exposed to 122 kRad(Si) with a Co-60 irradiator. The results here indicate that the gamma ray dose of 122 kRad(Si) was equivalent to 2.7E+9 n/cm**2 (1 MeV). The last line in Table 1 was corrected for fading of the neutron damage during the time of the Co-60 irradiation.

Table 1. Gamma-Ray Sensitivity

	#1	#2	#3	#4	#5
pre-exposure reading	1.549	1.547	1.550	1.549	1.550
122 kRad(Si)	1.575	1.573	1.570	-	-
2.4E+11 n/cm**2	4.443	4.369	4.371	4.324	4.382
122 kRad(Si)	4.475	4.386	-	4.351	-

8.0 1 MeV Equivalence

The diodes are intended to be used to measure 1 MeV equivalent neutron fluence. The sensitivity of the diodes to various neutron spectra was measured. This may be considered a calibration of the diode. It may also be considered as a verification of the 1 MeV equivalent response curve, since the diodes are silicon devices and the response curve is intended to predict damage to silicon devices.

Neutron energy-dependence tests were performed at two facilities. The National Institute of Standards and Technology (NIST) was used for thermal neutron calibrations, calibrations in 2, 25, and 144 kev beams, and calibrations with a bare and D2O moderated Cf-252 source. A 14 MeV neutron generator located at the US Naval Academy was used for the 14 MeV calibration.

The bare Cf-252 source was used to normalize the scale for 1 MeV equivalent fluence sensitivity. All diode results are reported based on this calibration.

Table 2 shows the neutron results from diode exposure in these neutron fields. For many of the fields, the diode voltage changes were quite small, both because of the low intensity of many of the sources and because of the small silicon damage constant for low-energy neutrons.

Table 2. Neutron Response to Various Sources.

Neutron Energy (kev)	Neutron Fluence (n/cm**2)	Diode Voltage Change (V)	1 MeV Damage (Mev-mb)	ASTM Damage (MeV-mb)	Measured / Predicted
thermal	1.71E+10(12%)	.001	0.6	-(a)	-
2	1.01E+11(7%)	.002	0.2	-	-
25	2.64E+10(10%)	.0025	1.0	1.9	0.5
144	1.78E+11(10%)	.030	1.7	2.9	0.6
14600	various	<2.0	237.	215.1	1.1
D2O	1.89E+10(5%)	.052	27.8	28.7(b)	0.97
Cf-252	various	5.5-6.2	112.	112.	1.00(c)

(a) ASTM damage function reports values only down to 10 kev neutron energy.
(b) Total non-thermal fluence used, not fluence greater than 10 kev.
(c) Cf-252 used for calibration. Ratio is 1.00 by definition.

The uncertainties in the three lowest-energy readings in Table 2 are quite large due to the low diode response to these neutrons. The values obtained are consistent with zero response to neutrons below 25 kev. Alternatively, the actual response could be a factor of two higher than measured.

The measurement at 144 kev is more significant. The value obtained should be within 20% of the correct value. The fact that it is not is probably due to the fact that 144 kev corresponds exactly to a sharp minimum in the neutron cross section in silicon. A silicon filter is used to produce the beam. The ASTM reported value is averaged over a range of energies, so it would be expected to be higher than the measured value.

The damage measured at 14.6 MeV is 10% higher than would be expected from the damage function. The discrepancy is even larger for more recent evaluations of the damage function of silicon. However, the uncertainty in the measured result is 30% due primarily to uncertainties in the monitoring of the 14.6 MeV neutrons.

The calibration in the D2O-moderated Californium source was done because the soft neutron spectrum (3) is typical of many environments where neutron testing is done. The agreement is excellent.

9.0 Calibration of the APRF

The intended use of the diodes is to calibrate the neutron fields in test facilities. Two exposure fields were calibrated at the APRF: 80 cm from core center on the Experiment Exposure Table (EET), and inside the glory hole. Both of these locations had 1 MeV to sulfur (fluence greater than 3 MeV) ratios measured previously (4,5). These were 8.2 and 8.4 for the EET and glory hole, respectively.

Diode measurements were performed simultaneously with sulfur measurements. Using the diodes to determine the 1 MeV equivalent fluences, ratios of 8.6 and 8.3 were found for the EET and glory hole. These results are consistent, considering 10% uncertainy in the original measurements and 9% uncertainty in the diode results.

10.0 Summary and Conclusions

The DN-156 diode has been evaluated for use as a 1 MeV equivalent neutron monitor in neutron fields produced at the APRF reactor. The values found with the diode are sensitive to the time after exposure and to the temperature of the readout; however, with care the diode can be used to measure 1 MeV equivalent fluence to 9%, traceable to NIST Cf-252 sources.

ACKNOWLEDGEMENTS

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1. ASTM E722-85, Standard Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics.

2. See DN-156 data sheet, available from Harshaw, for size and electrical specifications.

3. "Neutron Personnel Dosimetry", R.S. Schwartz, NBS Special Publication 250-12 (1987).

4. "Recalibration of APRF Neutron Dosimetry", C.R. Heimbach, Proc. of the Fast Burst Reactor Workshop, Albuquerque, NM, SAND87-0098, Vol. 2 (1987)

5. "Absolute Neutron-Flux Measurements at Fast Pulse Reactors with Calibration against Californium-252", E.D. McGarry, A.H. Kazi, G.S. Davis, D.M. Gilliam, IEEE Trans. Nucl. Sci., NS-23, NO. 6, pp 2002-2006 (1976)

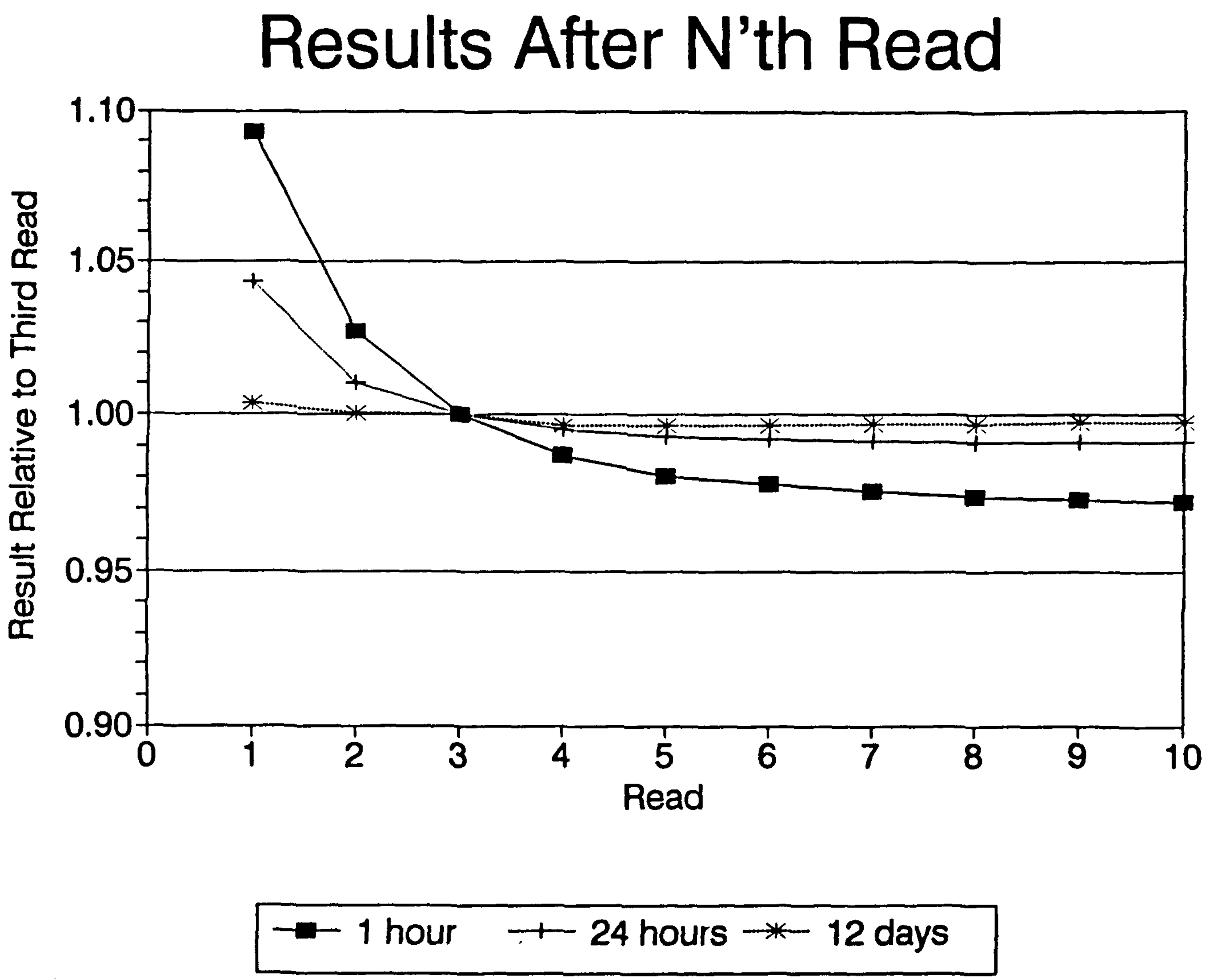

Figure 1. Relative diode readings versus reading number at various times after neutron exposure.

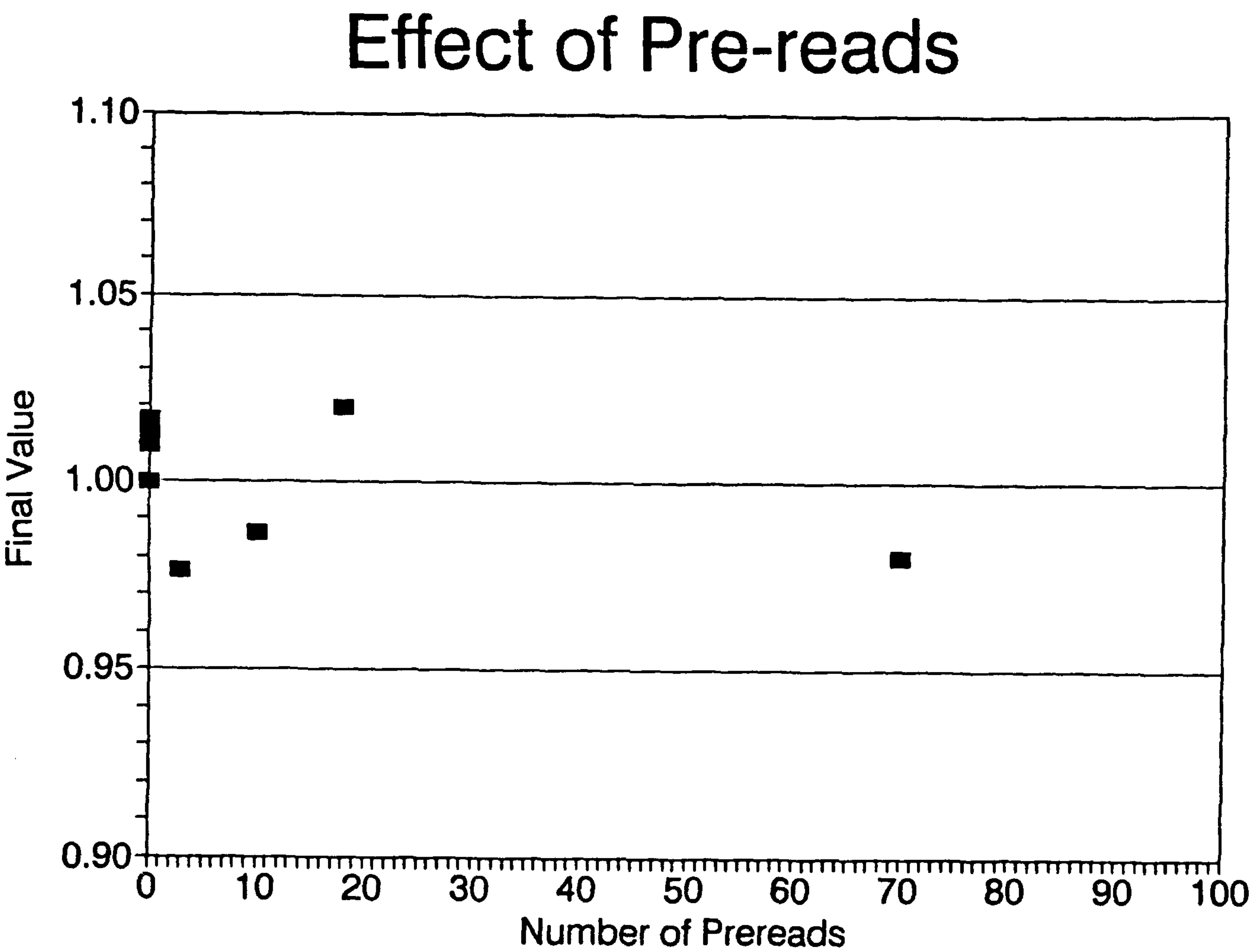

Figure 2. Relative diode reading versus number of prereads.

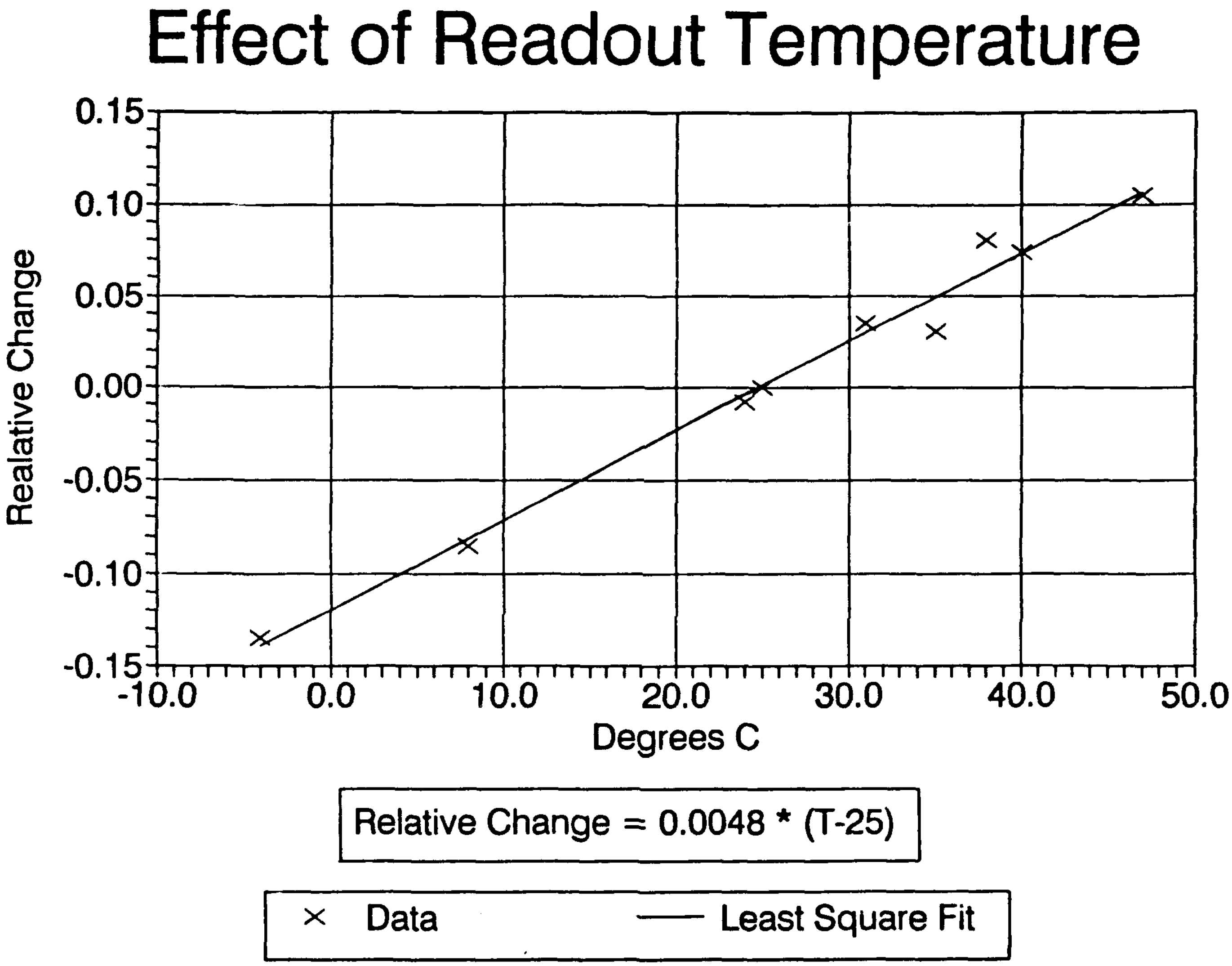

Figure 3. Effect of temperature at readout time on diode reading.

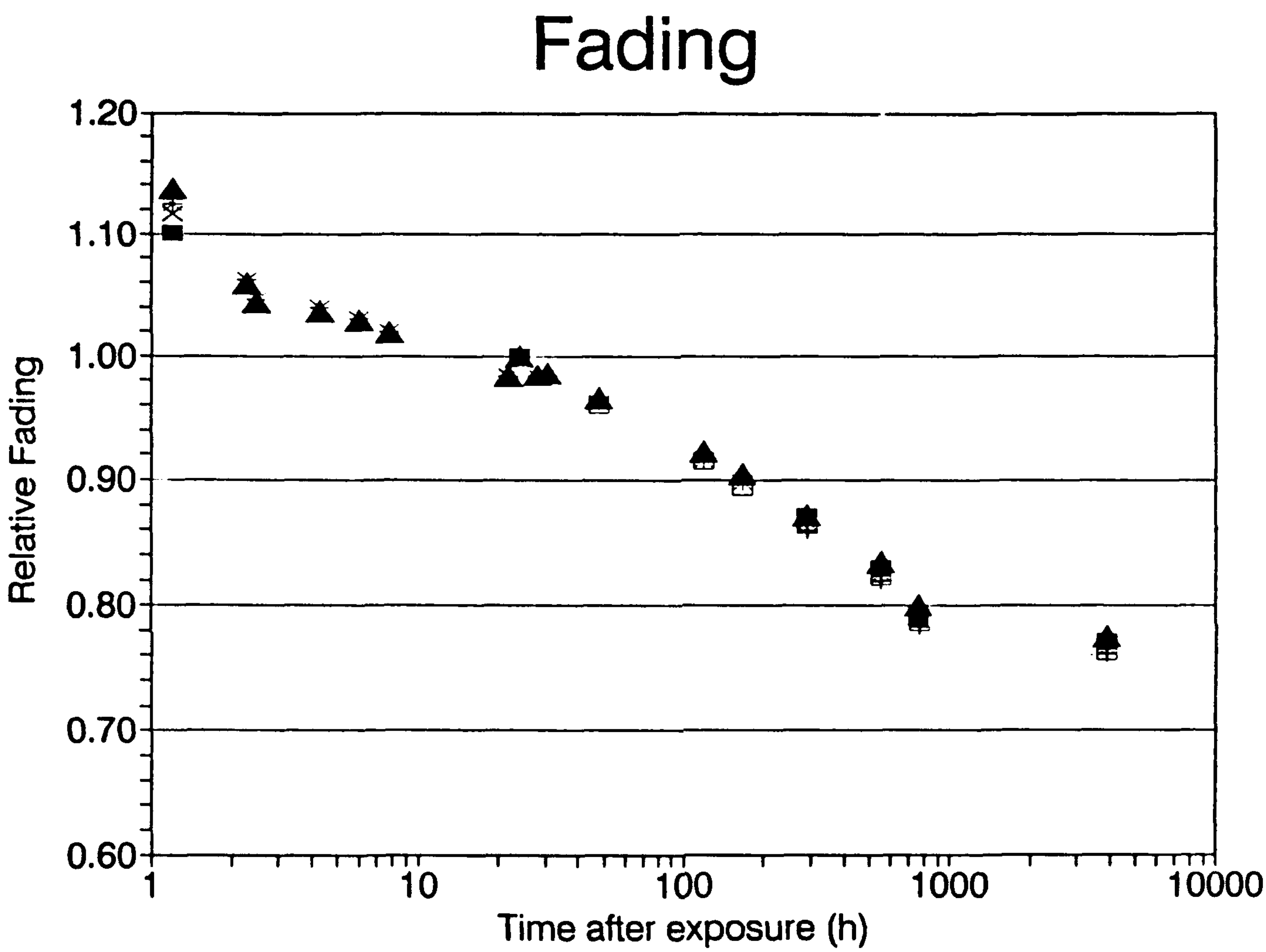

Figure 4. Diode fading.

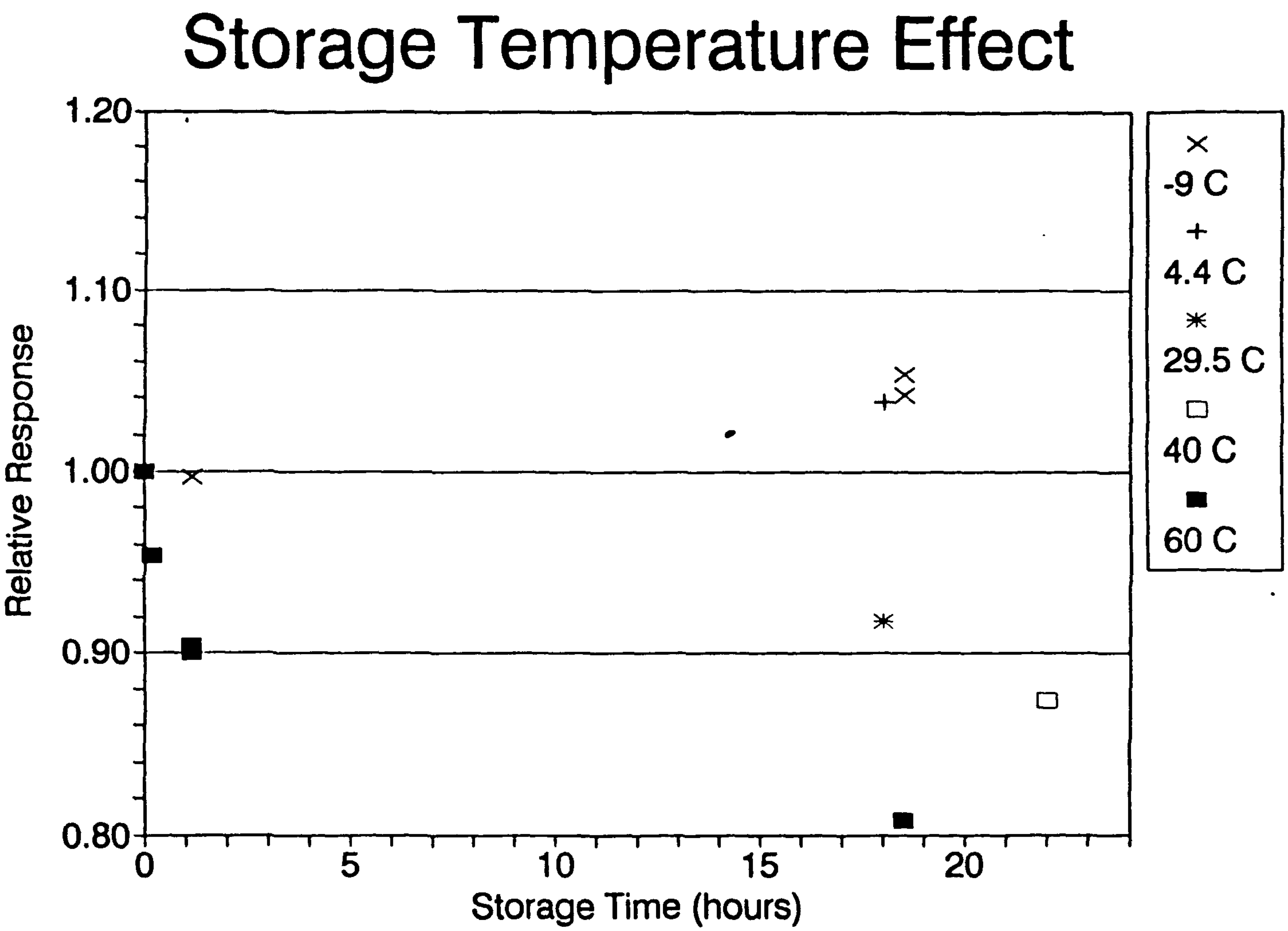

Figure 5. Effect of storage temperature on diode response.

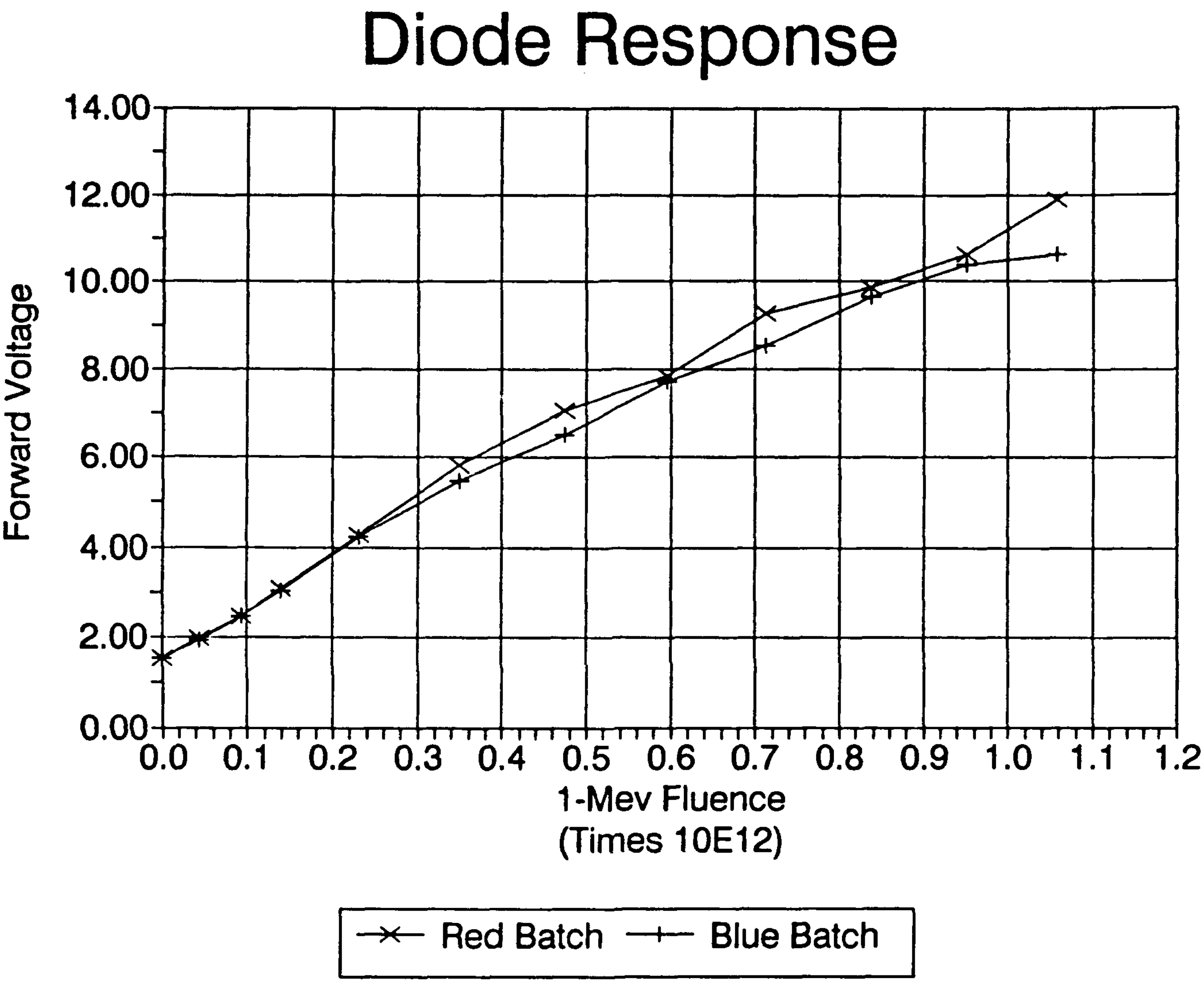

Figure 6. Calibration curves for two diode batches.

INVESTIGATION OF VARIOUS DIODES AS NEUTRON MONITORS

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1.0 Introduction

One diode, the DN-156, has been identified as a likely candidate for use a neutron monitor. In case this device proved unsuitable, other devices were investigated. The DN-156 worked out quite well, so that the other devices were not pursued.

2.0 Results

Several diode types were procured. The first requirement was that they respond to neutrons. The results are given in Table 1.

Table 1. Diode results for exposure to 9.0E+13 neutrons.

Diode Type	Initial V_F (Volts)	Final V_F (Volts)
1N4150	.735	.736
ECG553	.852	.794
1N4148	.795	.789
1N4005	.709	3.289
1N4001	.715	.990
1N4007	.632	.851
1N3600	.745	.741
1N914	.775	.790

where V_F is the forward voltage measured during a 6 millisec, 6 milliamp current pulse.

Several of the diodes proved radiation hard. This made them unsuitable as dosimeters. The 1N4005, 1N4001, and 1N4007 are possible candidates as alternatives to the DN-156.

3.0 Conclusions

Several diodes were evaluated as alternatives to the DN-156. A few showed potential, but, because of the success of the DN-156, they were not fully explored. The work with the DN-156 showed how this might be done, should the need arise.

Encl 2

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